THE FUNCTION OF INTRA-ARTICULAR FIBROCARTILAGES, WITH SPECIAL REFERENCE TO THE KNEE AND INFERIOR RADIO-ULNAR JOINTS

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The structures known as intra-articular fibrocartilages, or menisci, appear with remarkable constancy in the joints to which they are assigned by descriptive anatomy; not only in Man but also in other animals. They are therefore to be looked upon as integral parts of such joints, with definite parts to play in their workings. Nevertheless, they are undoubtedly often very variable as regards their size in a particular articulation: a disc stated to divide a cavity into two separate chambers is often found to be perforated to a great extent, and that without any apparent lessening of joint effectiveness. Further, it is a well-known fact that the removal of the internal meniscus of the knee is an operation not necessarily followed by discomfort of the patient in the use of the limb. There exists, then, the paradox that structures clearly of great importance for the normal working of a part can be removed (at least to the extent of one-half) without the production of ill effects. This paper is an attempt to present an account of the working of the intra-articular cartilages in terms of certain simple physical principles which are fundamental in joint mechanism, and which explain the effects of their absence as well.

PREVIOUS VIEWS

A survey of the literature available shows that attempted explanations of menisci[1] are morphological and functional. While the two are necessary for a complete understanding of any organ, they may be studied to a great extent independently. It is the second explanation which alone is treated of here. From the morphological side many different interpretations have been advanced: that they are structures *sui generis*; that they often represent elements of the skeletons of lower forms; and that they stand for tendons or ligaments taken into the synovial cavity (Bland Sutton, 1897). In their less ateleological moments, however, anatomists have paid some attention to possible reasons for the persistence of such remnants of a former glory. A summary may be given of the opinions expressed in the various English text-books. Either in the general or in the special sections of arthrology it is maintained that a

[1] The term "meniscus" is employed throughout this paper as a convenient term for an intra-articular fibrocartilage, without regard to the actual shape it may have in a particular instance.

meniscus (1) allows of dissimilar motions in the same joint; or, (2) abolishes the effects of incongruity between the male and female surfaces; or, (3) does both. Emphasis is usually laid upon the second of these rôles. It is assumed that the flexibility of the cartilage must obviously serve the purpose of fitting the surfaces together. This is also the opinion of Fick (1904, 1910), and it is seemingly still unquestioned in Germany (e.g. Broesike-Mair, 1930). (The latter textbook refers to the opinion of the brothers Weber that the menisci of the knee stand to the femur in the relation of wedges placed beneath a carriage wheel.) Goodsir's views on the matter will be taken up later; it is now pointed out that he adhered to the opinion that the disparity of the femoral and the tibial apposed surfaces was compensated by the elasticity of the interposed cartilages (Goodsir, 1858). Veterinary anatomists would appear to share these views. Sisson (1917) adheres to them explicitly, and adds that they help to prevent concussion. The last function had previously been ascribed to them by European workers.

Wood-Jones (1920) has criticised these explanations. He points out that all the Mammals (except monotremes) have a meniscus in the temporo-mandibular joint, even where only one kind of movement is permitted; and adduces the sterno-clavicular articulation as another example where distinct movements cannot be reasonably predicated of the two chambers formed by a meniscus. In regard to the congruence theory he says: "It is difficult to believe that Nature could not fashion the articulating bones to make an accurately fitting joint, and so adopted a plan of inserting washers to complete the adjustment"; and quotes Poirier's observation on the matter: "Cette explication de l'existence des fibrocartilages interarticulaires est loin de me satisfaire." It is a teleological answer to a teleological argument, and as such is quite pertinent to the discussion. As for the anti-concussional hypothesis, it is vitiated (in the writer's eyes) by the absence of menisci from such articulations as those of the talus, at least from the point of first importance.

FUNDAMENTAL PROBLEMS OF JOINT MECHANISM

The attempts which have hitherto been made to assess the working value of the menisci have this in common: that they assume them to be primarily related to the articular surfaces. These are large compared with the cartilages. It is here advanced as a principle of analysis, that in the interpretation of function parts of like dimensions[1] should be brought into association before the correlations with larger or smaller parts are sought for. There is one element of a diarthrosis which is of dimensions comparable to those of a meniscus—the synovial fluid. In practically all cases, the menisci divide the synovial fluid into roughly equal parts, each of which (by reason of the wedge-like form of the disc) is of comparable volume to the cartilage, that is, in the uninflamed joint. There will, then, be some positions in which the bones will be separated by a triple layer consisting of two films of synovia with a wedge of fibrocartilage

[1] The term "dimensions" may be taken either in the sense of absolute size, or with the meaning assigned to it by theoretical physics: length, mass, or time.

between. The first effect of an angular displacement of the laminar part of the meniscus will be an alteration of the relative thicknesses of the films: one will be increased and the other decreased in like proportion. Hence there will be a definite change in the character of the layers interposed between the bones; and it is of importance to determine the nature and effects of such an alteration, and the conditions in which it is likely to occur. It is convenient to deal with the second problem first, for it is merely another way of asking the question: in what circumstances are the bones entirely separated by the interposition of a synovial film?

In the construction of a diarthrosis two requirements have to be met. It must be possible for it to transmit weight through a temporarily stabilised couple, the components of which are displaceable, and it must permit of the free movement of the components on one another by the action of the related muscles (Walmsley, 1928). In a lecture delivered before the British Orthopaedic Association meeting at Belfast (in 1927) Prof. Walmsley summarised the main mechanical features of this class of joint. Following Goodsir, he developed the thesis that in the performance of the first function the joint surfaces are fully congruent and the articulation is in effect a synarthrosis, the synovial cavity being obliterated over the area of contact. In other positions they are incongruent. In the carrying out of the second function, therefore, a receiving (female) surface is continuously fitted by a male surface until the two are wholly congruent (that is, in movement towards the weight-bearing position: in movement from this position the surfaces will become more and more incongruent and they will separate to a greater degree). This had already been demonstrated at the knee (Bruce Young), at the atlanto-axial joints (Fick), and at the elbow (Hultkrantz). It was demonstrated by Walmsley at the hip, and has since been observed at the radio-ulnar joints (MacConaill, *infra*). The accessory articular mechanisms which bring about the synarthroidal disposition of diarthroses in the weight-carrying state are inactive in the function of movement. While in motion the epiphyses are not only rotated on each other but there is linear advancement of one area on another, so that the centre of rotation and the axis of rotation are always changing (Walmsley).

In the analysis just quoted attention was mainly directed to the terminal aspects of intra-articular relations. Further it was pointed out that no direct comparison was to be instituted between artificial and natural joints, in so far as the surfaces of the former tended to a maximal degree of congruence in all positions. There is no doubt that the usual constructions of the wheelwright and similar artisans do imply that the centres of rotation of the male surfaces are coincident with the centres of curvature (and, therefore, of rotation) of the corresponding female surfaces. The same is true of the models described by Fick for the elucidation of articular function (1910, *op. cit.*). It happens, however, that a body of knowledge has been accumulated by engineers concerning the actual internal state of fully lubricated joints in motion, from which important principles directly applicable to natural joints have been derived. These principles follow directly from some simple properties of viscous fluids in contact with moving surfaces, and have been applied with conspicuous success to the solution of many difficulties of the practical engineer. Their importance for the present discussion lies in the leading place they assign to the shape of the lubricant film. They show that it has an active, not a passive rôle in the play of forces engendered by movement; they indicate the circumstances in which a special apparatus is necessary for its effective maintenance; and they explain why this apparatus may sometimes be removed without apparent result upon the working of the part.

FUGITIVE ELASTICITY AND ITS EFFECTS

In a classical paper on "The Theory of Lubrication," Osborne Reynolds (1886) showed that the most effective form of lubrication depends upon the formation of a liquid film between the moving surface and its bearing. When this articulation (as an anatomist may call it) is at rest the surfaces are in contact so far as their shapes permit, and no fluid intervenes between them. If the bearing be flooded with oil the condition of free movement is that it shall come to lie between the fixed and moving surfaces in such a way that it can transmit the thrust from one to the other. This entails the setting up of a pressure in the fluid between the surfaces, of a magnitude equal to the thrust of one towards the other, but opposed in direction to it. A film exhibiting such a counter-thrust is known as a pressure film. Prof. Reynolds found that a viscous fluid in such a system displays a characteristic reaction to motion. It develops an elasticity which may be regarded as breaking down at short intervals of time, and is consequently known as "fugitive elasticity." The effect of this reaction upon the movement of the surfaces depends upon their relative inclination. If they be parallel, the forces set up act to oppose the motion and to drag the fixed surface after the moving one. Moreover, the liquid develops no pressure to counter a thrust forcing the surfaces together. Hence, oil tends to be forced from between such surfaces rather than to be carried into the gap which separates them. Should one of the surfaces be inclined to the other at a small angle (fig. 1), then motion in the direction of the narrow end of the wedge-shaped space thus formed causes the development of a positive pressure in the fluid[1]. This pressure begins just beyond the inlet for fluid and attains its maximum on the outlet side of the centre line (CC', fig. 1). The pressure has a twofold effect. It resists a thrust tending to force the surfaces together, and it forces lubricant through the outlet end of the gap. More lubricant will thus be drawn in through the inlet and a continuous supply assured so long as motion continues. The centre of pressure of the system lies between the area of maximum pressure and the line of centres. The load (weight-bearing) line passes through this point.

[1] In this and following descriptions the "horizontal" surface may be taken to be the moving one. Either surface may be in motion relative to the other, however: the important thing is that the two be inclined to each other in the direction of motion of the moving one. This motion would be parallel to the moving surface.

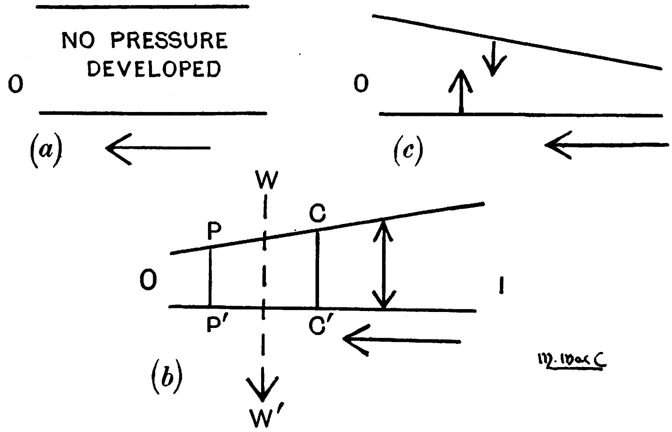

Fig. 1. The effect of the shape of a lubricant film on the forces set up within the liquid. (a) Surfaces parallel. (b) Surfaces inclined at a small angle. (c) Surfaces inclined at the same angle but movement in the opposite direction. I, inlet of lubricant. O, outlet of the same. The moving surface and direction of its motion are indicated by a horizontal arrow. Forces generated within the liquid are indicated by appropriate vertical arrows. In (b): PP', line of greatest pressure; CC', line of centres of surfaces; WW', position assumed by load line (line of resultant of all pressures).

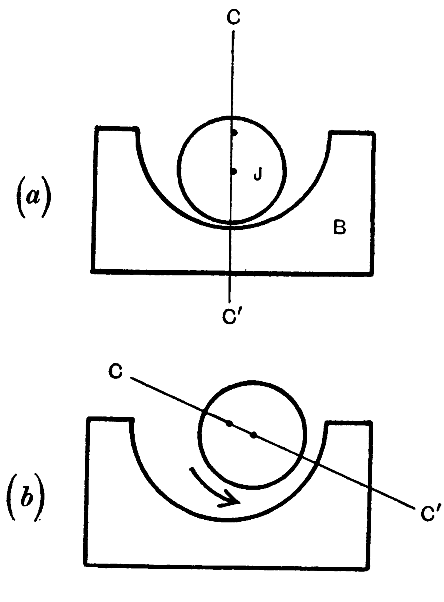

Fig. 2. Beauchamp Tower's experiment. (a) A journal (J) at rest relative to a brass (B) makes as close contact as possible with the brass, no lubricant intervening over the area of contact. (b) When the journal rotates relatively to the brass it sets itself eccentrically, forming a wedge-shaped space between it and the brass. Observe the direction of motion. CC', line of centres of B and J.

Motion towards the wider end of the cuneiform space tends to draw the surfaces definitely together and to force lubricant from between them. The liquid is forced against the motion and lubrication is interfered with.

From these facts it follows that movement between plane, or approximately plane, elements of a joint requires the formation of a *wedge* of synovia if they are to transmit weight or other thrusts during movement. The wedge must be convergent in the direction of motion, so that fluid may be drawn continuously between the surfaces, and the film maintained. It need only be of small angle. In the case of curved surfaces, Reynolds showed that the male surface automatically sets itself at the correct angle to the female during rotation, that is, if the bearing be flooded. This entails a shifting of the line of centres, and therefore of the weight-receiving area of the female surface during motion. These points are illustrated in fig. 2. It will be observed that the centre of the male surface—its axis of rotation—travels in the direction of motion. This was first recorded by Beauchamp Tower, from whom Reynolds obtained much of his data. Engineers usually provide for complete rotations of curved parts, and there is generally a close approximation between the male and female curvatures. This one-to-one correspondence is not so necessary in the bearings with which the anatomist has to do. In fact, it can be reserved for one position, the synarthroidal one, in which the apposed elements of the surfaces must fit closely together. In other phases of movement an incongruence of the parts is a positive advantage in the light of what has just been recorded. It ensures the formation of the wedge of synovia without which smooth movements are impossible. This is the key to the meaning of the inequalities of curvature upon which Goodsir laid such stress. Further, the shift in the axis of rotation to which reference has been made above is seen to be a physical necessity, even in the case of a well-turned artificial joint. Both features of joint motion are expressions of the readjustments necessary to maintain the important cuneiform film between the acting parts.

So far it has been assumed that the forces set up in the film are sufficient to balance the forces tending to thrust the surfaces together. The force of fugitive elasticity varies with the coefficient of viscosity of the liquid and to some extent with the rate of motion in the bearing. Should the axial thrust exceed a critical value the resistance of the fluid breaks down, and the surfaces are forced into damaging contact. This is the condition known to motorists as "seizing." It is often thought that it has but one cause: insufficiency of oil; but it can occur in the presence of an abundance of it. In the latter circumstance it occurs at high speeds, at which the longitudinal thrust of the shaft is of great moment. The same relative disproportion of oil reaction to thrust appears where a rise of temperature lowers the viscosity of the medium: that is, it is more prone to occur with fluids of low viscosity. In the majority of cases the surfaces are parallel. It has been shown above that such a disposition is not favourable to the formation of a pressure film.

THE MICHELL THRUST PAD

The principles enunciated by Osborne Reynolds, although recognised to be fundamental, were not applied to practice until the beginning of the present century, when an Australian engineer, Mr A. G. M. Michell[1], made use of them in the invention of the thrust block which bears his name. It was designed to meet the strains imposed by modern speeds on the bearings of marine engines. An examination of its essentials will make clear the function afterwards to be assigned to the menisci.

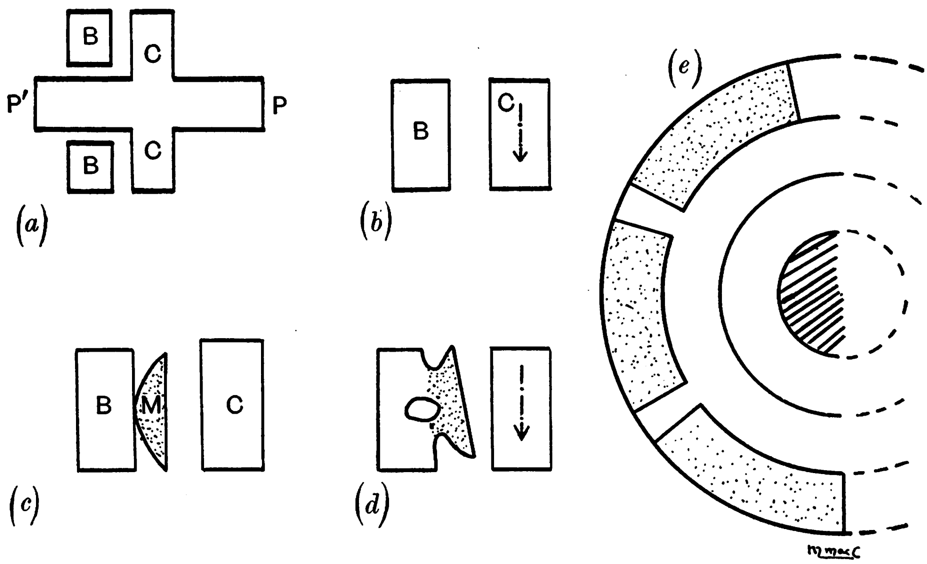

Fig. 3. (*a*) Section through a thrust bearing. *PP′*, propeller shaft. *C*, collar of metal shaft. *B*, thrust block. The thrust is in the direction *PP′*, the rotation through the plane of the paper. (*b*) Portions of block and collar to show that the motion is essentially between parallel surfaces. (*c*) Principle of the Michell thrust block. *M*, pivoted metal "pad," which can rock to-and-fro on the thrust block. (*d*) A Michell thrust pad (in this case connected to the block by deformable springs) sets itself automatically to the correct angle for smooth motion. (*e*) Surface view of a series of pads arranged to form a complete thrust bearing A horseshoe arrangement may be substituted.

A thrust bearing (fig. 3) consists of a block of metal pierced to allow passage to a rotating shaft. The reaction of the water on the propeller is transmitted to the thrust block by means of the metal collar, a film of oil separating the two while in motion. The bearing is flooded with oil, some of which is dragged between the block and collar by the movement of the latter. As both surfaces in apposition are plane they are also parallel. This entails a great liability of the film to break down at speeds well below the maximum attainable by the engine,

[1] A descendant of the Rev. John Michell who devised the method, and bequeathed to Henry Cavendish the apparatus, by which the latter determined the Constant of Gravitation.

and demands the provision of many such bearings to divide up the load. These add very much to the dead weight of the ship, an addition not repaid by the increase in efficiency. Mr Michell interposes a number of metal pads between block and collar. Each of these is sector-shaped in outline, with a plane collar face and a somewhat curved (convex) block face. The curvature of the block face permits the pad to rock through a small angle during motion; and accordingly it sets to the correct angle during movement of the collar, be this ahead or astern. Thus is ensured the formation and maintenance of the film wedge. It has been found that the connection between the pads and the block can be made by a double spring or some equally deformable continuous structure, since the deflection under the load has to be but a slight one. Such a flexible connection enables bearings to be simplified by constructing a number of pads integral with, but flexibly connected to, a common supporting member. A serious disadvantage is that the flexibility involves more or less risk of fracture of the flexible part, a danger which is overcome by giving flexibility to a portion of the pad itself (Michell, 1923).

These thrust bearings have proved very successful in practice. Their number can often be reduced to one, and other economies are effected by their use. In addition they allow of greater speeds, and are widely used to-day both in marine and land work in which high thrusts have to be met. Their purpose may be emphasised. They are employed where thrusts are to be carried by a film of lubricant during motions in which there is a considerable element of gliding, and in which a screw-like movement along the axis of thrust is discouraged.

THE MENISCI AS MICHELL PADS

A sector of a meniscus can be described as a wedge of elastic material, pivoted at its attached base, so that it is capable of some variation in its inclination to the articular surfaces with which it is in relation. The effect of such variation will be felt first by the synovial fluid: that is, the synovial film in contact with the articular surface will be made cuneiform to a greater or a less degree according to the amount of adjustment of the meniscus. Such angular deflections will be of small magnitude. Thus the sector is comparable in every respect to the most up-to-date type of Michell pad. The complete fibrocartilage is merely the integration of such elements, and may be of ring-, horseshoe-, or plate-like form. By reason of its flexibility, which is increased by the thinning of the central part, such a structure is easily affected by stresses in the synovia. The viscosity of this fluid is certainly not less than that of blood serum. Experiments are in progress regarding its actual value: but the table (see p. 218), which gives the viscosity of serum and of certain oils commonly used in film lubrication, will show that the requisite physical condition of the liquid for the application of Reynolds' laws to it is certainly present. The matter of the speed of the moving parts is dealt with below. (See further, p. 226.)

The synovial fluid, then, is one in which the phenomena of fugitive elasticity may be expected to appear, and the stresses set up in it by movements at the joint will be of a corresponding nature. The part of the cartilage in relation to the weight-transmitting surface of the bone (at the moment) must so arrange itself that a wedge of lubricant, convergent in the direction of movement, is formed between it and that surface. Thus will be brought about the effective transmission of weight from the fixed to the moving surface through the fluid during motion, a transference which demands in certain cases a special apparatus that it be maintained without detriment to the continued separation of the surfaces. In a word, the menisci serve to increase the incongruence of joint surfaces rather than to decrease it. In this respect they are to be compared to the accessory cartilages of the hip and shoulder, although the function of the latter is not quite that of the menisci.

This statement of their function makes it clear where they are to be expected. They are likely to be found where a thrust is combined with gliding and rotation, if the consequent screw-like motion of the parts towards one another is not of service in the movement: that is, if it tend to put the bones into premature contact. If the surfaces be of large radii of curvature such contact is more likely to occur than if they be more rounded. A comparison of the carpometacarpal joint of the thumb and the sterno-clavicular joint will serve as an

Liquid		Coefficient of viscosity (C.G.S. units)	
Blood-serum	(32° C.)	1·9	(Burns, 1929)
Bayonne oil	20° C.	1·6	Stanton, 1923
Rape oil	20° C.	0·90	Stanton, 1923
Sperm oil	20° C.	0·34	Stanton, 1923

illustration. The view here put forward approaches that put forward by Parsons (1899–1900): it differs from it in being arrived at from first principles of mechanics and in defining more rigorously the locus of the structures concerned. Parsons' theory associated intra-articular cartilages with a combination of gliding and rotatory movements, laying special stress on the rotatory element. The present one rather reverses the emphasis, and takes cognizance of the fact that such combinations are present in practically every diarthrosis in the body, as Goodsir and his followers have justly maintained. They are present in the hip and shoulder. Here, however, they give a helical path to the moving point, at least in the former case. In so far as this tends to force the bones into premature contact, the well-rounded form of the heads of the long bones causes them to assume a favourable disposition to the female surfaces, as has been indicated above in the reference to Beauchamp Tower's experiment. It is possible, however, that the ligamentum teres may play the part of a meniscus in the hip joint, its consistency and disposition being not unfavourable for that function.

It should be added with respect to Parsons' theory, that the form he gave it was scientifically correct. It was derived from a purely morphological study and summarised all the facts observed by him in a manner consistent with the physics of the time. Even yet, the principles of viscous-film lubrication are far from being widely known, except to certain classes of engineers; and the usual text-books of applied mechanics make but passing references to it. Those who are interested will find a full treatment in the article of Michell quoted above, and in Boswall (1928); while a simple presentation of its basal ideas is given by Edser (1926).

So far the treatment of the problem has been largely of an *a priori* nature with a view to establishing a reasonable hypothesis. It is not proposed to discuss all the joints which have intra-articular cartilages in what follows. The tibio-femoral and inferior radio-ulnar articulations have been selected as types for the demonstration and illustration of the lubricant function of the menisci. What is here proved for them holds for other joints; and in the ensuing discussion only certain of those others will be referred to as being of special interest.

KNEE JOINT

No detailed description of the form and attachments of the menisci is required. The points of importance for the elucidation of their function are: their wedge-like shape in section, the firm attachment of their cornua to the tibia, and the expansions of the vasti tendons which end upon them. A simple dissection is necessary to display the agreement of their relation to the bones with what has been premised above. The tibia is to be sawn through at the level of the upper part of its tuberosity. The cancellous tissue so exposed is to be removed carefully, and the deep surface of the compactum scraped clean. Holes should be drilled in the latter to emerge about the middle of the upper surface of each condyle. The openings are enlarged and the articular cartilage trimmed with scissors. The enlargement should be carried on until the lower surfaces of the menisci come into view. Care must be taken to keep their attachments intact, and it is well to be conservative of bone, so that a good estimate may be formed of the relations of cartilage and condyle in various phases of movement. A diagram of the views to be beheld through the "windows" is given in fig. 4. It was drawn by the aid of a camera lucida. In a like preparation the following facts may easily be observed:

Only in the position of full extension (with the proper rotation carried out) is there a complete congruence of the cartilages with the femur. In this, the "weight-carrying" position, the tibio-meniscal space is completely shut off from the femoro-meniscal; this applies to both condyles. In all other positions there is a wedge-shaped gap between bone and meniscus. These observations may be confirmed by an oil test. The bones are fixed in the weight-carrying position. The preparation is held so that the tibial windows look vertically upwards and the femur is below. Thin oil is poured into each opening. A pool is formed and remains for an indefinite time. In any other position whatsoever the oil passes from the tibio-meniscal to the femoro-meniscal chamber at once. Thin oil is chosen as it is a moderately viscous medium and its movements are easily observed. The experiment could be carried out with a watery fluid (albumen), but not in a specimen treated with oil; in this case surface-tension reactions between water and oil allow the liquid to slip through capillary spaces which would normally refuse passage to a viscous medium. The experiment shows that the menisci separate from the femur on the initiation of movement from the weight-bearing position in such a way that wedge-shaped spaces are formed between them and the bone, convergent in the direction of motion. The convergence will of course be noted for only one gap in each part of the double joint. If the corresponding part of the femur be marked it will be found to be that which is nearest to the tibia at the instant: it is the momentary weight-transmitting area. It has been shown by Michell and his school that the conditions of film lubrication are fulfilled if the weight-transmitting area be in contact with a convergent film—the disposition of the film elsewhere is not of importance. In extension, therefore, the anterior part of the cartilage is in

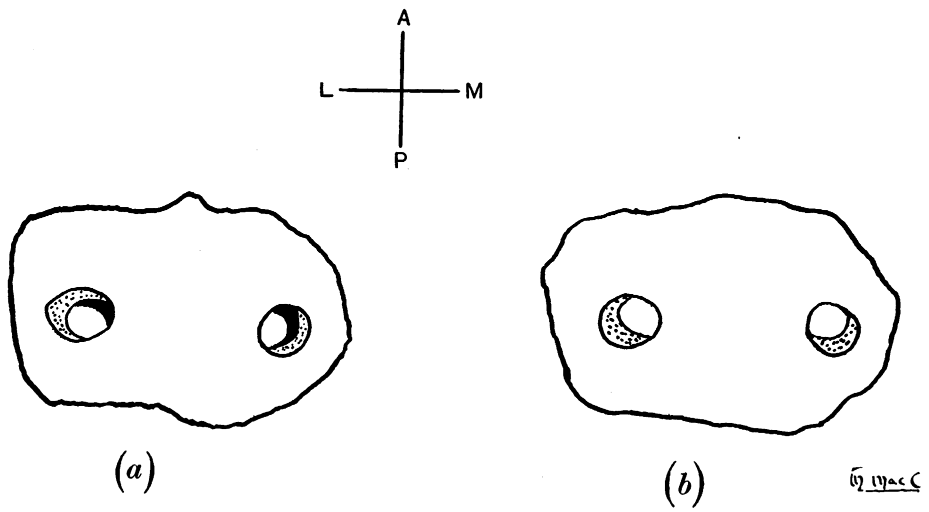

Fig. 4. Diagrams of knee joint from below, viewed through openings in the tibial condyles. The menisci are stippled. (*a*) in semi-flexion. (*b*) in full extension.

action as an aid to weight transmission; and fluid is carried from the patellar aspect of the femur to the under aspect, through the cuneiform gap. In flexion it is the posterior part, and in the rotatory movement, the lateral part that comes into effective play.

The meniscus, in short, behaves like a series of Michell pads welded into a generalised form, which is called for by the more complex movements of the animal joint. They are called for by the compound movement in which the gliding or sliding element is large in proportion to the rotatory. This does not permit of the self-adjustment which takes place between the components of a more purely spherical or hinge-like articulation. The "set" of the cartilage is largely automatic, and is conditioned by the forces generated within the fluid by movement. It should here be pointed out that the speed of the moving surface is of importance in the formation of a pressure-film. It must have a minimal value of the order of 38 mm. (1·5 in.) per second. Experiments made by the writer on the living show that these velocity conditions are fulfilled at the knee: the least speed at which *smooth* motion is attainable having at least twice the critical value. The same, it may be added, holds for other joints. The function of the cartilage is assisted by its attachments to the tibia and to the vasti expansions. These bring about a tension of the meniscus and of its capsular attachment, so that it can take the fluid counter-thrust and pivot into the required angle. As movement continues, the cartilages move forwards independently of the tibia, for in a well-lubricated specimen it can be observed that their motion is markedly accelerated. In part this motion is

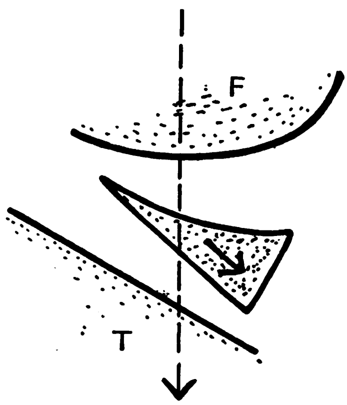

Fig. 5. A diagramt o illustrate the action of the menisci of the knee. *F*, an element of the femoral surface. *T*, an element of the tibial surface. The knee is moving from the semi-flexed to the extended position, and the motion of the cartilage relative to the tibia is indicated by the arrow within it. Femur and cartilage are, of course, moving in different directions. The direction of weight transmission is indicated by the broken arrow (load line). It will be observed to pass through the outlet (narrow) parts of the synovial wedges between the various moving surfaces.

due to reaction between the meniscus and the pressure-film of synovia, and it is a witness to the existence of the latter. Thus, as the flattened parts of the femur come into contact with the tibia, the cartilages are shot forwards with a twofold effect: the bones are permitted to come into direct relationship, and the posterior parts of the menisci are brought into contact with the femur, completing the separation of the upper and lower chambers of the joint (fig. 4). These effects are furthered by the opposite rotations of the cartilages described in the text-books. The posterior part of the cartilage is now "convergent" with respect to a femur about to undergo flexion. The whole mechanism is a very beautiful one, and the "wonder of the knee joint" is increased rather than diminished by a knowledge of the underlying simplicity of action. Fig. 5 illustrates in diagrammatic form the essential action of the cartilages as the femur moves from the semi-flexed to the extended position, as in walking. The separation and angulation of the parts are, of course, exaggerated for the sake of clearness. The tilt of the cartilage relative to the tibia is to be specially noted. This tilt ensures the transmission of pressure from meniscus to tibia through the outlet end of the menisco-tibial synovial wedge.

With regard to the semilunar form of the menisci, it is of interest to note that horseshoe arrangements of Michell pads are quite commonly substituted for the annular disposition. Further, the larger size and more open form of the internal cartilage are precisely what are demanded by an application of the Michell principle, assuming that the most efficient lubrication be called for. Again, it has been shown that the total bearing surface of a Michell pad may be reduced to about half of the total possible area without inefficiency. The dimensions of the menisci of the knee, relative to the total effective articular surface at a given instant, are quite in keeping with this standard. Moreover, the occasional failure of the cartilages to perforate is no bar to a reasonably efficient action, since the elastic plate can function as a whole as it does, for example, in the temporo-mandibular joint (*infra*). In this "mass action" it is helped by the attachments of the vasti expansions. It is a corollary of the last affirmation that perforation of a cartilage which is normally complete is not necessarily disadvantageous, since the ring can function as a Michell pad system, provided that the reduction of surface does not appreciably exceed one-half. Rarely, in the writer's experience, does it go beyond that amount.

It remains, in connection with the knee joint, to account for the common absence of symptoms following the removal of a semilunar cartilage. The cartilages are accessories to lubrication, they might almost be called refinements on the part of Nature. Those in whom a violent effort provokes fracture of a meniscus—an accident previously explained to be conditioned by their flexibility—are persons of athletic habit. French surgeons, indeed, have noted a great increase of the number of such injuries since the introduction of "Anglo-Saxon" games—notably football (Jeanbrau, 1921). Loss of a meniscus leads to about 20 per cent. increase in friction. This amount is not usually reached in any but violent efforts—and the increased strain is likely to be unnoticed at a critical point in the game by a man in training. But it is recognised if ill-health supervene, and is remarked by those who have taken up exercise after a prolonged sedentary period, as the writer has verified. Many surgeons have recorded the incidence of osteo-arthritic changes in several of their cases, a result in keeping with the increased liability to premature contact of the articular surfaces of the bones on account of the removal of the counter-pressure set up by the synovial wedge.

INFERIOR RADIO-ULNAR JOINT

The inferior radio-ulnar joint is distinguished from the superior by the gliding character of the movement associated with it: a distinction which is emphasised by the wholly fleshy structure of its proper pronator. The triangular fibrocartilage is to be reckoned an accessory to this joint. The very full researches of Parsons (1899) have shown that the degree to which it is developed is positively correlated with the movement of supination, and that its best representative is to be found in Man. There are certain details of its structure and attachments which have to do with its function and demand preliminary notice; and some attention must also be given to both joints with regard to the position in which they assume the relationships characteristic of a synarthrosis, that is, in which they transmit weight directly from one component to the other.

The triangular cartilage follows the rule in that it is thicker circumferentially than centrally. The thinning is often stated to be central: but is more accurately described as centroidal—it is nearer the base than the apex of the triangle. When the thin part is perforated the greater part of the remainder bears a great resemblance to a semilunar cartilage. This likeness is heightened by the roundness of the angles of the cartilage proper. The disc is obliquely disposed between radius and ulna, sloping downwards and inwards from base to apex. Both surfaces are moderately concave, the greatest depression being, of course, at the spot already styled the "centroid" of the triangle.

SYNARTHROIDAL POSITION OF JOINTS OF FOREARM

Upper. The head of the radius is not circular but elliptical in outline. In a typical specimen the major axis is 2·4 cm. and the minor, 2·25 cm. This applies to the cartilage-encrusted bone. The curvature of the corresponding cavity of the ulna is equal to that at the extremity of the major axis of caput radii. Elsewhere the curvature of the male (radial) surface is less than that of the female (ulnar) surface. If a fresh joint preparation be examined from above, the annular and interosseous ligaments being intact, the synarthroidal position can be determined to be nearly half-way between pronation and supination. In this phase of rotation the head of the radius is most accurately adapted to the ulna, the long axis of its curvature being at right angles to the ulnar shaft, the shafts of the bones are most widely separated, and the interosseous membrane is at its greatest tension. The membrane is not quite taut: the significance of this fact will be discussed in a later paper dealing with the problems of weight carriage in the forearm. In any other position there is a small, but distinct, gap between the lesser sigmoid cavity and the head of the radius; this space is angular, and convergent in the direction of motion at the instant.

Lower. In many cases the triangular fibrocartilage is perforated: where this occurs a view of the relations of the head of the ulna to the radial articular surface is afforded. It can easily be determined that the head of the ulna is most closely applied to the radial concavity at the same phase of movement as brings about maximum congruence of the elements of the upper joint. Each of the radio-ulnar joints is a virtual synarthrosis at the same instant, about midway between pronation and supination; and this is the definition of the weight-carrying position of the forearm.

THE MOVEMENTS OF THE FIBROCARTILAGE

A perforation of the triangular fibrocartilage is, in effect, a window for the inferior radio-ulnar joint similar to those made by dissection for the tibio-femoral. The opening is usually small, but it is large enough for the observation of the varying relationships of the ulnar head and cartilage. Only in one position does the rounded head of the ulna rest upon the disc in such a way as to occlude the opening—that position is the weight carrying one. In all others it is separated by a wedge-shaped space from the disc. The oil test is effective here, and demonstrates the complete congruence of bone and cartilage in the mid-prone stage of motion. If a little fluid be introduced into the joint cavity while it is in the fully supinated position it will be observed to be forced through that part of the wedge-shaped space which is convergent in the direction of motion; small air bubbles make its direction clearer. This shows the identity of the conditions in this joint with those in the knee, and with those set up by a Michell thrust pad.

The cartilage is, in fact, such a pad inserted between the hand and ulna. It enables weight to be transmitted from the hand to the ulna during movement of the radius across the forearm. This joint also illustrates the function of the congruence of the menisci with their proper bony opposites: it cuts off the flow of fluid and automatically brings the surfaces into direct play. It is to be noted that the path of the lower end of the radius is not a simple turn, but is a compound of sliding and rotation about the ulna of a somewhat helical kind.

COMPARATIVE ANATOMY

The comparative anatomy of these structures is quite well known as the result of Parsons' researches, and such an authority as Fick accepts them in their entirety. The writer has been able to verify them in such animals as were available, and the discussion of this part of the subject will be simplified by taking Parsons' accounts as standard descriptions. Reference need only be made to the knee, temporo-mandibular, and ankle joints to show the efficiency of the present explanation in satisfying the postulates laid down above.

Menisci are found in the knee joint as low down in the vertebrate scale as the amphibia (Bland Sutton). In Mammals the bat is unique in that it has not a trace of them. In this animal the joint is a pure ginglymus, rotation being prevented by a bony spur. In the English bat (*Vespertilio*) the tibial spur is very striking. In one form (*Plecotus*) a small amount of rotation is allowed, and delicate menisci are developed. More information is required on the landing movements of these creatures as the weight-carrying parts of their skeleton must differ both in site and development from those of non-flying Mammals.

In the lower monkeys the movement of rotation is better developed than in Man, and occurs even in the semi-flexed position. In such animals the semi-lunar cartilages are better marked, especially the outer. This is probably to be correlated with their swinging habits, which would tend to throw much strain on the knee, unless the latter were made more yielding in its movements than those of heavier types.

The temporo-mandibular joint is the classical example of the double-movement theory. It is not denied that such a double motion is found there, nor that the articular disc is a valuable accessory to it. But the forces which mould the flat articular eminence from infancy onward could equally well make one compatible with the condyle of the jaw, while still retaining its gliding movement. The existence of the disc in the carnivora furnishes an anatomical Voltaire with an excellent text against the "sufficient reason" of the theory. The difficulty disappears if the work of such discs in opposing a counter-pressure to that of the food be borne in mind. Although the trituration factor is absent from the carnivorous mandibular thrust, the tearing stress replaces it in importance; and it is necessary that the bearing surfaces be not prematurely forced together during the action of the carnassials. Intra-articular cartilages are not found in the jaw joints of the Monotremata, and they are likewise missing in certain of the Marsupalia (*Dasypus, Dasyurus*). Parsons has put forward the theory that the discus is a new mammalian acquisition, and thus accounts for its absence in these lowly forms. This view is not unacceptable: but further work is needed on the masticatory function of these animals before the absence of the structure can be held to be accounted for on functional grounds. It may be that such an explanation is unnecessary, as one covering positive instances can admit a phylogenetic account of origins.

The marsupials have a fibrocartilage between the astragulus and the fibula. It is to be correlated with the power of the fibula to rotate on its long axis (Parsons). The writer is inclined to associate its presence in the kangaroo with the strain thrown on the ankle at the termination of the leap; and in all these forms, the kangaroo and wallaby excepted, the fibula is very movable on the tibia and is liable to be drawn inwards by the tibio-fibular muscle.

DISCUSSION

The facts of human and comparative anatomy, so far as they have been recorded, seem to be in agreement with the thesis that the function of intra-articular cartilages is to maintain a convergent film of synovia between those bones the necessary movement of which is prejudicial to their continued separation during motion. This view of their working is in accord with the postulates of physics with regard to the transference of force between fully lubricated moving surfaces. It provides an explanation of their presence for the instances in which they occur. The only case of absence from a higher mammalian group is reconcilable with considerations of habit; and a *prima facie* case is recorded for an evolutionary reason of their non-appearance in monotremes and certain marsupials. The congruence hypothesis has been shown experimentally, as well as theoretically, to be untenable. Goodsir recognised that the incongruence of articular surfaces of such joints as the knee must leave gaps between the bones. He deduced therefrom that the menisci and synovial pads had the common function of filling up the spaces. He definitely associated the cartilages with localities of pressure, making out that the other structures were found to occupy spaces free from strain. He was not aware of the laws of lubrication—they were not known in his time: nevertheless, in correlating the menisci with pressure, he made a good approximation to the truth. It may be said that the present essay is in some sort an extension of the principles he put forward regarding articular movements. The work of Prof. Parsons has already been referred to in the body of this paper—it is hoped, not unjustly. The difference between the points of view is largely one of emphasis. Finally, it may be said that an anti-concussional effect is not to be entirely ruled out. In many cases intra-articular cartilages must serve such a purpose: but only as a secondary result of their primary action.

SUMMARY

It is shown by reference to the theory of lubrication that intra-articular fibrocartilages are to be related primarily to the synovial fluid rather than to the articular surfaces of the bones. They act to bring about the formation of wedge-shaped films of synovia in relation to the weight transmitting parts of joints in movement. These wedges are narrowed in the direction of motion, and are necessary for weight transmission. They are to be found in joints where thrusts are likely to bring about a premature approximation of the joint surfaces. Preparations are described of knee and inferior radio-ulnar joints, which demonstrate the action of such cartilages. These also show that the cartilages are congruent with articular surfaces only in the "weight-carrying" position of the joints.

I wish to put on record my appreciation of the interest in, and encouragement of this work by Prof. Patten; and my thanks to Dr N. K. Adam, late Sorby Fellow of this University, for references to early papers on the theory of lubrication.

ADDENDUM

The experiments referred to on page 217 above have now been completed. They show that the viscosity of human synovial fluid is of the order of 10 C.G.S. units, at 20° C. This value is five times as great as that of blood-serum, but might fall as low as 7 units at body temperature. Accepting the latter value, it can be calculated that the thickness of the synovial film (knee) is of the order 50μ. Such a value is in full accordance with the principles set out above. Details of the experiments and of the calculations based thereon will be given in a future paper.

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